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Magnetic Resonance Neurographic and Clinical Long-Term Results After Oberlin's Transfer for Adult Brachial Plexus Injuries

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Abstract: The primary goal of the surgical treatment of upper brachial plexus injuries is to restore active elbow flexion. Accordingly, Oberlin's transfer has been frequently performed since 1994 and has influenced the development of other nerve transfers. However, the window of opportunity for nerve transfers remains a subject of controversy. The objective of this study was to assess magnetic resonance (MR) neurographic, clinical and electrophysiological long-term results after Oberlin's transfer. For this purpose, we performed a retrospective follow-up study. Six patients with upper brachial plexus or musculocutaneous nerve injuries were assessed; 2 were iatrogenic nerve injuries following shoulder arthroscopy or neurofibroma resection. Direct and indirect signs of neuropathy were objectified with MR neurography. Moreover, clinical and electrodiagnostic follow-up was performed and all patients completed the Disabilities of Arm, Shoulder and Hand score. Mean follow-up was 48 ± 21.9 (range, 20–73) months. Mean age was 40 ± 11.3 years and mean delay to surgery was 9 ± 3.2 months. All patients were satisfied with the functional results and the median Disabilities of Arm, Shoulder and Hand score was 21 (range, 1–57). Biceps strength was improved in 5 patients from Medical Research Council grade M0 to M4-5 and in one patient to M2-3. The donor nerve showed normal motor and sensory action potentials. Follow-up MR neurography demonstrated biceps reinnervation. Taken together, this study reports good long-term results after Oberlin's transfer. MR neurography represents an excellent, noninvasive preoperative planning tool and can be of high value in selected postoperative cases. The combined evaluation of nerves and muscles may help to indicate nerve transfers in delayed cases.

Key Words: brachial plexus injury, MRI, MR neurography, nerve transfer, musculocutaneous nerve injury, reinnervation

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Upper brachial plexus injuries are rare but devastating injuries. They frequently affect young male patients after traction injuries in traffic accidents.[1,2] The primary goal of surgical treatment is to restore active elbow flexion. The management of brachial plexus injuries has markedly evolved after the introduction of peripheral nerve transfers. Due to short reinnervation distance, beneficial muscle synergism and the possibility of selective motor fascicle harvest, these transfers represent a cornerstone in reconstructive brachial plexus surgery.[3] Oberlin et al[4] described the partial ulnar to biceps nerve transfer to power active elbow flexion without jeopardizing the function of the donor nerve. This procedure (Oberlin I) has been frequently used ever since and influenced the development of other intraplexual and extraplexual nerve transfers. Moreover, several case series have reported good functional results of this transfer, both for adult[2,4–10] and obstetric[11,12] upper brachial plexus palsies.

After denervation, muscles are expected to undergo atrophy within 12 to 18 months.[13] Corresponding to this biological process, nerve transfers close to the target muscle can be performed after the often-quoted time frame of 6 months.[14] However, the window of opportunity for nerve transfers remains a subject of controversy.

Besides the improvement of the surgical technique, new useful imaging modalities have been developed. Magnetic resonance (MR) imaging of the peripheral nerves, referred to as MR neurography, is of special interest in brachial plexus trauma. Of note, rapid advances in coil technology and software development led to an exceptional anatomical resolution, making this modality able to both detect and grade nerve injuries.[15,16] For example, nerve injuries are characterized by increased T2 signal intensity, reflecting processes as vascular congestion, increased endoneural fluid or Wallerian degeneration.[17] In line with this advances, preoperative MR neurography has become widely accepted as a noninvasive diagnostic tool among brachial plexus surgeons and radiologists.[18,19]

In the present study, we assessed the functional and electrophysiological results after Oberlin's transfer for adult brachial plexus injuries. In addition, MR neurographic follow-up including the whole brachial plexus from root level to the motor branch of the musculocutaneous nerve was performed.

METHODS

Study Design

We performed a retrospective follow-up study. Research ethics board approval was obtained (KEK-ZH-Nr. 2013-0384). Consecutive patients from 2006 to 2012 undergoing Oberlin's transfer were included and assessed with electromyography (EMG) and nerve conduction studies (NCS) (Fig. 1). Exclusion criteria were (1) previous injury to the contralateral arm, (2) a follow-up less than 12 months, and (3) inflammatory nerve pathologies (ie, Parsonage-Turner syndrome[20]). One nonblinded neurologist repetitively performed electrodiagnostic testing and the preoperative and postoperative strength assessments for all patients. The maneuvers were performed in full supination to reduce brachioradialis-powered elbow flexion. Moreover, we used the Disabilities of Arm, Shoulder and Hand (DASH) questionnaire to analyze residual functional impairment at the latest follow-up. The DASH is a subjective 30-item disability rating scale, resulting in scores between 0 (no disability) and 100 (maximal disability).[21] There were no preoperative DASH scores available. Finally, patients eligible for MR studies were examined with MR neurography. Exclusion criteria for MR neurography were (1) gravidity, (2) contrast agent allergy, (3) non–MRI-compatible pacemakers or cochlea implants, and (4) claustrophobia.

Patient and Injury Characteristics

Six patients were included in this study. Patient characteristics are shown in Table 1. Mean age was 40 ± 11.3 years, the mean follow-up was 48 ± 21.9 months (range, 20–73), and the mean delay to surgery was 9 ± 3.2 months. Case 5 showed the longest interval between injury and surgery with 15 months. The Oberlin's transfer was

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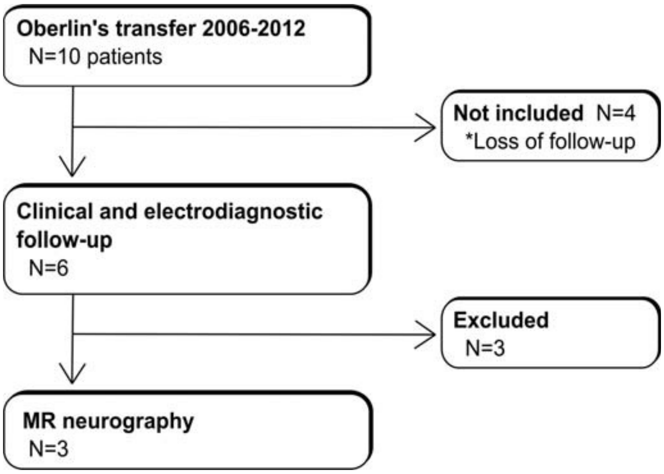

FIGURE 1. Patient selection process.

performed after partial ulnar nerve recovery following posttraumatic brachial plexus neurolysis.

Surgical Procedure

The surgical technique has been described in detail by previous authors.[2,7] We performed the transfer in an end-to-end technique with perineural 10/0 monofilament polyamide (S&T AG, Neuhausen, Switzerland). We used intraoperative nerve stimulation to identify the fascicles innervating the flexor carpi ulnaris and to avoid denervation of the ulnar intrinsics. All trauma patients underwent brachial plexus exploration. Four patients were treated with Oberlin I, and 1 patient received a double transfer, that is, Oberlin I and triceps to axillary transfer (Table 1). Moreover, 1 triple transfer with additional cranial nerve XI to suprascapular nerve neurotization was performed. Finally, this case required a trapezius muscle transfer to power shoulder reanimation.

Electrodiagnostic Studies

Serial EMG studies were conducted preoperatively and postoperatively. All electrodiagnostic studies were performed on an EMG machine (Viking EDX, Natus, Pleasanton, USA) by the same neurologist. The goal of the electrodiagnostic examination was to quantify reinnervation of the biceps and to exclude neurogenic damage in the donor nerve territory. For this purpose, we performed antidromic neurography stimulating the ulnar nerve at the axillary level and recording over the motor point of the biceps muscle using surface electrodes. To exclude donor site damage, we performed motor ulnar neurography with surface electrodes recording over the abductor digiti minimi muscle and antidromic sensory ulnar neurography with ring electrodes on the fifth finger. Motor potentials were recorded in mV, sensory potentials in μV. The patients were subjected to needle EMG recordings using concentric needle electrodes (Natus, USA).

MR Neurography

Three male patients (mean age, 46 years) were included for MR imaging. All subjects underwent bilateral imaging, whereas the healthy arm was scanned first and the arm with the nerve transfer consecutively. Care was taken to ensure correct and identical positioning of the participants throughout the study. Therefore, a coauthor of this study was present at all scans and confirmed the correct positioning.

Imaging Protocol

The MR imaging was performed on a 3.0 Tesla Siemens Skyra system (Siemens Healthcare, Erlangen, Germany) using commercially available 20-channel head-neck coils as well as an 18-channel body coil (Siemens Healthcare). The imaging protocol included T1-weighted turbo spin echo (TSE) sequences in coronal and transversal orientation, a T2-weighted TSE Dixon sequence in transversal orientation and a T2-weighted sampling perfection with application of optimized contrasts using different flip angle evolution/short tau inversion recovery sequence in coronal orientation (see Table 2 for detailed sequence parameters). In addition, a single-shot EPI diffusion sequence with 12 different gradient directions at a b value of 800 s/mm^2 was performed in sagittal orientation with following imaging parameters: repetition time, 6000 ms; echo time, 65 ms; number of slices, 48; spatial resolution, $2.0 \times 2.0 \times 2.0$ mm; field of view, 150×84 mm; acquisition time, 7:50 minutes. After all sequences were completed for both arms, IV contrast material (gadoteric acid "Dotarem", Guerbet, Villepinte, France) was administered and a postcontrast T1-weighted TSE sequence with fat saturation in coronal orientation was performed for the arm where the Oberlin's transfer had been performed.

MR Image Analysis

Three nonblinded radiologists with experience in MR neurography evaluated the assessed images in consensus according to Chhabra et al.[17] In particular, following parameters of the bilateral peripheral nerves of interest were assessed: (1) size, (2) signal intensity, (3) fascicular pattern, (4) course of the nerve, (5) enhancement, (6) peripheral fat planes. Based on those criteria, the raters evaluated potential abnormalities of the peripheral nerves

TABLE 1. Patient Characteristics

Case	Age	Sex	Occupation	Trauma	Level	Delay to Surgery, mo	Surgical Procedures	Preoperative MRC Biceps	Postoperative MRC Biceps
1	42	m	Blue Collar	Iatrogenic	Lateral fascicle postganglionic	10	Oberlin I	M0	M5
2	36	f	White Collar	Polytrauma	C5-C7 root avulsion	6.5	Triple transfer* Trapezius-transfer	M0	M5
3	41	m	White Collar	Polytrauma	C5-C7 root avulsion	6.5	Double transfer†	M0	M4$^+$
4	58	m	White Collar	Iatrogenic	Musculocutaneous nerve	8	Oberlin I	M0	M5
5	37	m	White Collar	Polytrauma	Incomplete infraclavicular postganglionic	15	Oberlin I	M0	M2$^+$
6	23	m	White Collar	Polytrauma	C5-C6 incomplete postganglionic, C_7 root avulsion	8.5	Oberlin I	M0	M4$^+$

*Oberlin I, triceps to axillary nerve and cranial nerve XI to suprascapular nerve.

†Oberlin I and triceps to axillary nerve.

MRC, Medical Research Council grading; f, female; m, male.

TABLE 2. MR Neurography Protocol

	Sequence				
Characteristics	Coronal T1W TSE	Axial T1W TSE	Axial T2W DIXON	Coronal T2W SPACE STIR	Axial T1W TSE pKM* FS†
TR‡, ms	880	684	4900	2500	659
TE§, ms	9.1	9.0	84.0	193.0	9.0
No. slices	20	64	64	96	64
Slice thickness, mm	4.0	3.0	3.0	1.0	3.0
Resolution, mm × mm	0.6 × 0.6	0.7 × 0.7	0.7 × 0.7	0.9 × 0.9	0.7 × 0.7
FoV‖ acquisition matrix, mm × mm	307 × 512	272 × 320	320 × 320	304 × 320	272 × 320
Averages	1.0	1.0	2.0	1.4	1.0
Total scan duration	2:18	3:30	8:41	6:24	4:29

*Post contrast media administration.
†Fat saturated.
‡Repetition time.
§Echo time.
‖Field of view.
SPACE STIR, sampling perfection with application of optimized contrasts using different flip angle evolution/short tau inversion recovery.

on interest following Oberlin's transfer as compared with the healthy arm where no surgery had been performed.

Statistical Analysis

Data were tested for normal distribution and equal variance and differences between the 2 groups were analyzed using the unpaired Student *t* test (SigmaStat; Jandel Corporation, San Rafael, CA). All values were expressed as means ± standard SD. Statistical significance was set for values of P less than 0.05.

RESULTS

Functional Results

All patients were satisfied with the functional results and would undergo surgery again. Accordingly, the median DASH score at follow-up was 21 points (range, 1–57). For 3 patients, we recorded Medical Research Council grade M5, 2 had $M4^+$ and 1 patient showed recovery from M0 to $M2^+$. The patient with the lowest postoperative Medical Research Council grade ($M2^+$) reported a DASH score of 23 points.

Electrodiagnostic Results

Biceps reinnervation was analyzed by means of antidromic motor ulnar neurography. The mean distal motor latency recorded for the reinnervated muscle (5.9 ± 1.9 ms) was significantly slower compared with the healthy arm. In addition, the mean amplitude of the operated side (3.5 ± 2.5 mV) was significantly lower (Fig. 2). However, the values were within the expected range for a neurotized nerve. Electromyography showed normal reinnervation for 2 cases. There were no clinical or electrophysiological signs of ulnar nerve damage except for case 5, who suffered from preoperative partial ulnar nerve injury. The mean amplitude of the hypothenar intrinsics for the remaining 5 patients was 10.6 ± 1.9 mV, and the mean sensory nerve action potential was 15.2 ± 8.1 μV.

Follow-Up MR Neurography

MR neurography allowed precise anatomical illustration of the brachial plexus and the musculocutaneus nerve (Figs. 3 and 4). Of interest, MR neurographic analyses revealed persistently increased T2 signal intensity of the musculocutaneous nerve proximal to the Oberlin's transfer (Fig. 5). Because of postoperative susceptibility artifacts and the fact that with even multichannel receiver coils, only a limited signal-to-noise

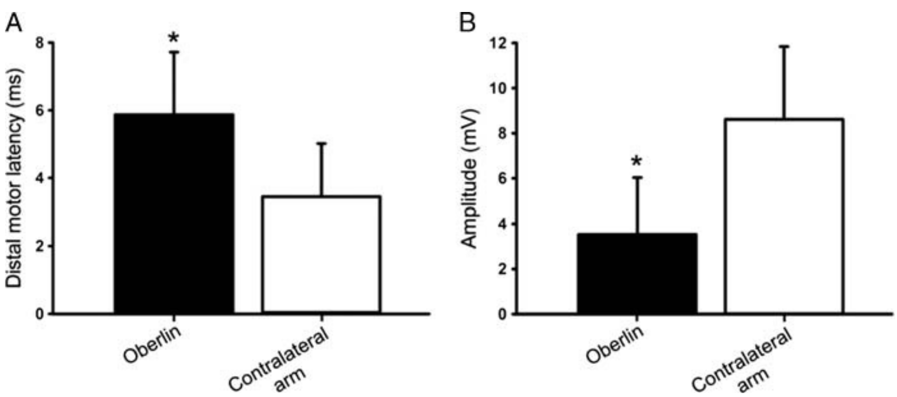

FIGURE 2. Electrophysiological results after Oberlin's transfer. Distal motor latency (A) and amplitude (B) of the Oberlin's transfer (black bars) assessed by means of antidromic motor ulnar neurography in comparison to the contralateral musculocutaneous nerve (white bars). Mean ± SD (n=6); *$P < 0.05$ vs contralateral arm.

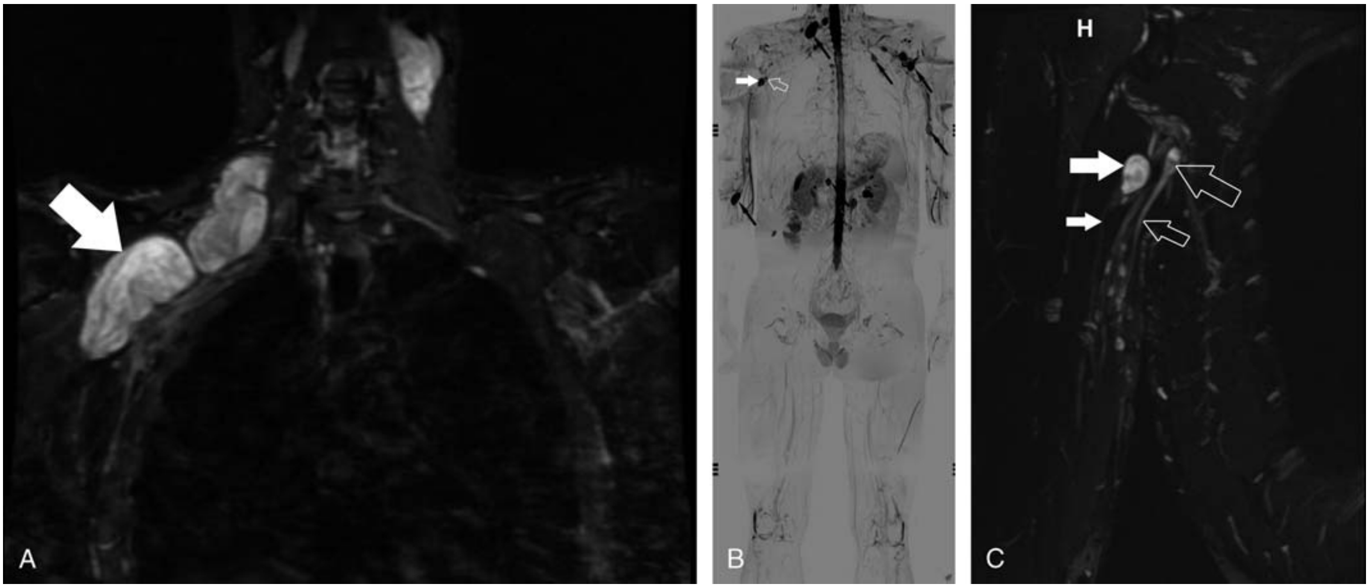

FIGURE 3. A 42-year-old man with neurofibromatosis II. A, Coronal fat-suppressed T2-weighted MR image shows an extensive neurofibroma (arrow) of the right brachial plexus. After initial tumor resection, the patient complained loss of elbow flexion. EMG/NCS showed partial lateral fascicle injury. The Oberlin's transfer was performed to treat musculocutaneus nerve deficit. B, Postoperative follow-up MR image of the whole body 4 years later identifies multiple neurofibromas (some of which are exemplarily marked by small black arrows) as well as two recurrent neurofibromas in the lateral plexus (open and white arrow) of the operated right side. C, Dedicated brachial plexus MR neurography after 6 years provides detailed view, showing that the neurofibromas arise from the musculocutaneous (white arrows) and ulnar nerve (open arrows). Despite the recurrent neurofibromas the patient had an excellent outcome with biceps strength M5 and a DASH score of 1. H, humeral head.

ratio and hence limited resolution could be reached, visualization of the transferred nerve as well as the biceps branches distal to the anastomosis was challenging even though state-of-the-art 3.0 Tesla MR systems were used. Instead, the target organ (biceps muscle) was successfully assessed for signs of denervation, that is, for atrophy or fatty replacement.

DISCUSSION

Oberlin's Transfer

The treatment of upper brachial plexus injuries with intraplexual and extraplexual nerve transfers is the standard approach in our division. Both root avulsions and postganglionic injuries can be approached with nerve transfers. In addition, we routinely perform nerve grafting in line with Bertelli and Ghizoni, who had the best results for C5-C6 injuries with a combination of grafting and triple transfers.[22] Good indications for grafting include postganglionic Sunderland[23] forth-degree and fifth-degree injuries.

The functional results of our study are comparable with the excellent results after the Oberlin's transfer published by previous authors.[2,3,6–8,24–27] With average 9 months delay to surgery, this small series confirms the recently published good results after delayed transfers.[26] We agree with Khalifa et al[27] that good results can be expected as long as the neurotizing nerve reaches the end effectors within 18 months after denervation. However, the window of opportunity to perform the transfer remains a subject of discussion. Good results have even been reported up to 24 months after injury.[26] In fact, the short reinnervation distance of the Oberlin's transfer encourages attempts of late reconstruction. Moreover, we observed normal postoperative ulnar nerve function except for case 5 and electrodiagnostic follow-up confirmed this finding. Facing this good risk-benefit ratio, the Oberlin's transfer is an attractive salvage option for delayed presented brachial plexus injuries. Furthermore, case 5 (delay to surgery 15 months) did not show atrophy or fatty replacement of the biceps muscle on follow-up MR imaging, which supports the theory of successful late neurotization. In addition, the electrophysiological integrity of the transfer was demonstrated.

We have performed the Oberlin's procedure for 3 C5-C7 injuries. These patients regained good elbow flexion (M4+ or M5) and reported low functional disability with DASH scores of 14, 48, and 57, respectively. Comparing the median DASH score of all six patients (21 points) with the normative values of the general population (mean, 10.1 ± 14.7 points) assessed by Hunsaker et al,[28] the impairment of daily living activities was marginal. Accordingly, all patients would undergo surgery again and were satisfied with the functional results.

Shoulder stability is an important prerequisite for good elbow function,[8] and all patients were able to stabilize the glenohumeral joint at the latest follow-up. Terzis and Barbitsioti[8] identified factors that influence the outcome of elbow function restoration. Besides the type and level of injury, denervation time and patient age, intraplexual nerve transfers were significantly associated with better functional outcomes than extraplexual transfers. This highlights the importance of synergistic donor nerves. Ali et al[29] recently published an excellent review about nerve grafting, nerve transfers, and their combination for postganglionic upper trunk injuries. Three hundred Oberlin's transfers were included in this analysis and provided significantly better results than other surgeries.

MR Neurography—Added Value for the Brachial Plexus Surgeon?

Most clinical studies on Oberlin's transfer included preoperative electrodiagnostic studies and CT myelography. Today, MR neurography is accepted as the standard preoperative imaging tool because it is noninvasive and allows precise and qualitative documentation of the whole brachial plexus.[17] Tagliafico et al[30] found high accuracy of MR neurography with surgical findings in brachial plexus trauma (sensitivity, 0.84;

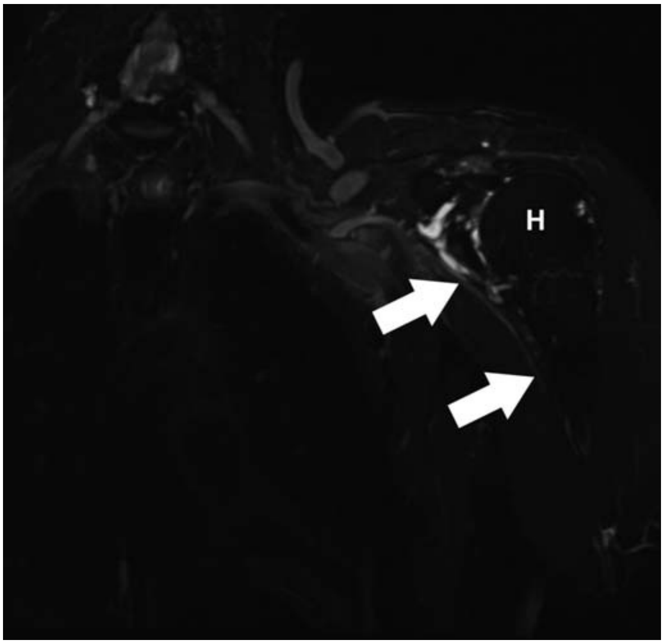

FIGURE 4. T2-weighted, fat suppressed coronal image of the left brachial plexus of a 58-year-old man provides illustrative overview of the normal course of the musculocutaneous nerve (arrows). Note that the nerve can typically be visualized until the proximal portion of the upper arm where it divides into motor side branches to the biceps muscle. H, humeral head.

specificity, 0.91). Accordingly, high-resolution MR neurography with improved 3D imaging and fat suppression provides detailed anatomical delineation of the brachial plexus and therefore the site of nerve injury and its severity. The Sunderland classification has been correlated to MR neurography findings.[31] Whereas electrodiagnostic studies can distinguish between neurapraxia (conduction block) and higher-degree injuries (≥ Sunderland II, axonotmesis), MR neurography provides the surgeon with more detailed information about the injured nerve segment. Of interest, it may help discriminating between Sunderland third- and forth-degree lesions. Sunderland II and III injuries remain a field of controversy and can be approached with watchful waiting, whereas Sunderland grade IV and V should undergo surgery as soon as possible as these injuries do not show spontaneous regeneration.

In addition to nerve imaging, the denervated muscles are evaluated for indirect signs of neuropathy. These can be detected on standard MR sequences. Months to years after injury, the muscles become atrophic, which results in fibrosis and fatty replacement. This condition hampers reconstructive plexus surgery with nerve grafting or transfers. Hence, salvage procedures, such as tendon transfers or free functional muscle transfers, represent the only reconstructive strategy. As the time span between injury and muscle degeneration is not reliably predictable, MR imaging may be used as a decision aid when planning delayed plexus reconstruction.

We routinely perform preoperative MR neurography around 4 weeks after injury as the traumatic soft tissue edema has mostly diminished by then, allowing an accurate identification of injured nerves. MR neurography is extremely useful in long-time intubated patients, but a high index of suspicion is required not to miss brachial plexus trauma in the unconscious patient.

We have performed postoperative MR neurography in this study. It has proven very useful in selective cases as tumor-associated nerve injury, where recurrent disease can be monitored and further surgery anticipated (Fig. 3). Moreover, follow-up MR neurography can reproducibly objectify the results of brachial plexus surgery by direct (T2 signal intensity of nerves) and indirect (muscle degeneration) signs of neuropathy. Here, we have documented normal MR findings of the biceps muscle after the Oberlin's transfer as assessed with anatomical imaging. It is to note that in the current study, we did not calculate visual representations of the peripheral nerves in terms of diffusion tensor imaging tractography based on the measured diffusion images.[32] Although diffusion tensor imaging tractography is a powerful method to illustrate peripheral[33] or even cranial[34] nerves, the signal-to-noise ratio, and hence spatial resolution achievable on clinical MR systems at 3.0 Tesla in a postoperative setting with susceptibility artifacts being present, is not sufficient to fully depict all neuronal structures involved in Oberlin's transfer. Furthermore, we did not evaluate potential alterations of the muscle's diffusion properties after Oberlin´s transfer, such as mean diffusivity (MD) (ie, a value for the total diffusion within a voxel which is a assumed to be a surrogate for membrane density). In general, MD values have been shown to represent sensitive parameters detecting even subtle muscle changes, such as subclinical sports-related alterations, which might remain undetected by conventional T2-weighted MR imaging applying fat suppression.[35] Nevertheless, we did not perform MD analysis for following reasons: on one hand, the assessed group with 3 participants was too small to calculate statistical parameters that would have been required to infer on potential alterations in MD. On the other hand, because we aimed to present the current results in a comprehensible and replicable way for clinicians, we assessed functional, electrophysiological, and MR neurographic parameters using methods that are broadly available. Drawbacks of follow-up

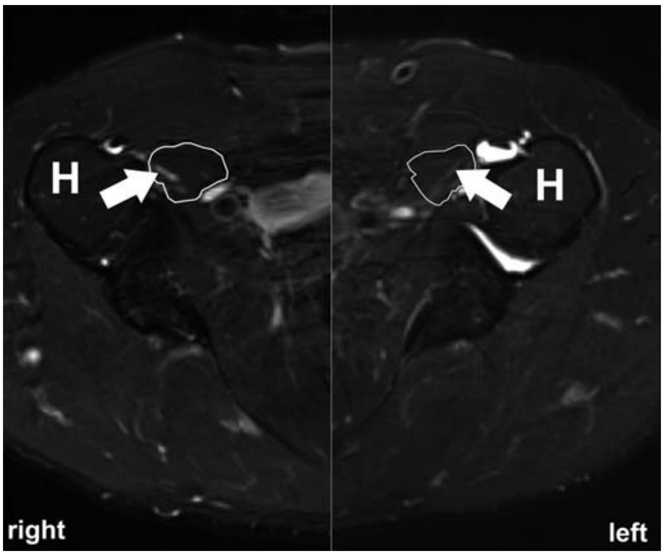

FIGURE 5. A 58-year-old patient 6 years after Oberlin's transfer. The transfer was performed to treat complete musculocutaneous nerve injury after shoulder arthroscopy for rotatory cuff reconstruction. Axial fat-suppressed T2-weighted MR image of the normal left and operated right side shows persistent thickening of the right musculocutaneous nerve (arrow) as well as neurogenic edema with increased T2 signal intensity proximal to the anastomosis at the level where the nerves courses within the short head of the biceps muscle (encircled). The absence of neurogenic muscle edema or biceps atrophy is indicative of a functional recovery. The clinical findings (biceps M5, DASH score, 18) correlated with the MR imaging of the muscle. H, humeral head.

MR neurography are long examination time and the potential need of IV contrast agents.

Inherent to any study are limitations. First, our study was of retrospective nature. Second, one major problem in measuring and comparing outcomes of brachial plexus surgery is the heterogeneity of the injury pattern due to the complex anatomy. Accordingly, our series included isolated iatrogenic musculocutaneous nerve and traumatic brachial plexus injuries.

Taken together, the Oberlin's transfer provided good results for neurotization of both upper brachial plexus and isolated musculocutaneous nerve injuries. Moreover, MR neurography is extremely valuable in the preoperative decision making. The combined evaluation of nerves and muscles may help to indicate nerve transfers in delayed cases. However, postoperative MR neurography is reserved for special cases as tumor-associated nerve injury but can be of use in clinically or electrodiagnostically inconclusive cases.

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